Damage in steel bars applied for civil construction submitted to corrosion

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Abstract: *A study was developed about corrosion and degradation of the mechanical properties in steel bars used in civil construction and a simplified model for the evolution of the damage in these bars was developed through the Continuum Damage Mechanics Theory. Steel bars specimens were confectioned and submitted to an accelerated corrosion test (Salt Spray) being displayed in this corrosion chamber for different intervals of time. After the corrosion test, the specimens were submitted to the mechanical test of traction with loading and unloading, getting the elasticity modulus for each unloading. Then, the concept of measure of damage through the variation of the Elasticity Modulus, introduced by LEMAITRE, was applied. The damage in function of the deformation for each specimen was obtained. Finally, with the analysis of the damage in the different specimen, the variable Damage in function of the mechanical loading and the corrosion was written.*

Keywords: Corrosion, Continuum Damage Mechanics***,*** reinforced concrete

1. Introduction

Nowadays, there are a lot of kinds of materials used in civil construction, for instance, metals, timbers, plastics and others. However, one of the most used certainly is the reinforced concrete, which is composed by steel rebars and a matrix of concrete. This material is largely used on building constructions for its mechanical properties and low cost of manufacture.

The first application of the steel rebars, in the concrete, occurred in 1850, in France, by Joseph Lambot (KAEFER, 1998), where Lambot used steel rebars and a mesh of wires, in a concrete boat. This experience was very important to increase the application field of the concrete that was limited for some properties. Loadings as bending were enough to promote a fracture in the material, because the concrete is a fragile material. However, with the addition of the steel rebars, this material shows now ductility and avoids the excessive opening of the fissures. In this way, the reinforced concrete could be used in many applications of the civil construction.

As any structure that uses metallic components, it is also subjected to the corrosion, which is responsible for many structural failures. Although the concrete to act as a protection, for its high pH, is common to occur corrosion of the rebars due fissures and pores that allow the access of substances that react with the steel as chloride.

One of the ways to evaluate the effects of the degradation is through the Continuum Damage Mechanics (CDM). The CDM is the study, through mechanical variables, of the mechanisms involved in this deterioration when the materials are subjected to loading (LEMAITRE, 1996).

The purpose of this paper is to measure the damage in steel bars subjected to corrosion, through the variation of Elasticity Modulus.

2. Corrosion in Reinforced Concrete

It is fundamental to occur the corrosion process, in the steel bars, the presence of a electrolyte, a difference of electrode potential and oxygen. The absence of one of these elements will hinder the beginning of the corrosion or will cease the process, it is case already in progress (HELENE**,** 1986).

- Electrolyte – the water is always present in concrete, and many times in amounts enough to act as electrolyte, acting in the transport of the necessary ions to the reactions of electrochemical corrosion.
- Difference of electrode potential – the difference of humidity, aeration, saline concentration, tension in the steel, it can generate a difference of electrode potential capable to create electrochemical cells.
- Oxygen – it is necessary to have oxygen for formation of the rust, product of corrosion, as for instance:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \tag{1}$$

When correctly executed the concrete protects the steel bars about two aspects: the physical and chemical. The chemical protection results of high pH existing in the watery solution present in the pores of the concrete that allows the formation of a protective film. It is known as passivation layer. This film presents low ionic conductivity, low solubility and good adherence to the steel. The passivity is kept due the high alkalinity of the solution of the pores, pH between 12.5 and 13.5. This elevated alkalinity is due to the calcium hydroxide $Ca(OH)_2$, proceeding from the reactions of hydration of the cement.

In these conditions, for this pH around 12.5, according to Pourbaix, cited for (FORTES**,** 1995), the reactions of electrode verified are of passivation. Thus, the steel bars in the interior of the concrete are protected from corrosion.

However, this film can be destroyed, for the carbonation or the presence of aggressive agents as: chlorides – Cl, sulfides, nitrates and sulfur oxide.

2.1 Action of Ions Chlorides

Even though the concrete does not have chlorides, they can reach the steel rebar, through the pores or fissures, when these structures are in sea atmosphere or another environment that contains chlorides. Depending on the aggressiveness of the environment, the corrosion can reach dangerous speeds of deterioration.

The transport of chlorides, as other liquids, in the interior of the concrete is influenced by the pore structure of the cement paste. Thus, the interconnection of the pores and the distribution of the size are important factors. The opened pore allows the transport of substances and characterizes the permeability of the cement. On the hand, the size of the pores influences the transport speed (CASCUDO**,** 1997).

The chlorides can be carried in the concrete through the capillary absorption mechanism, diffusion, permeability and migration.

2.2 Carbonation

When the concrete is exposed to the acid gases, as the carbonic acid gas (CO_2), the sulfur dioxide (SO_2) and hydrogen sulphide (H_2S), the pH can be reduced.

The transformation process of the cement compounds in carbonates, for the action of the carbonic acid gas, is called carbonation.

The carbonation process of the concrete occurs slowly, according the principal reaction:

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O \qquad (2)$$

With the loss of passivity, the cell of electrochemical corrosion develops itself, being able to cause damages to the structure. The corrosion, beyond provokes the reduction of the metallic area, its products can occupy volume of various times bigger than the original volume of the steel rebar, being able to cause expansion pressure of until 15 MPa (GENTIL, 1996), that will cause the fissuration of the concrete, as shown in fig.1, will affect the structural stability.

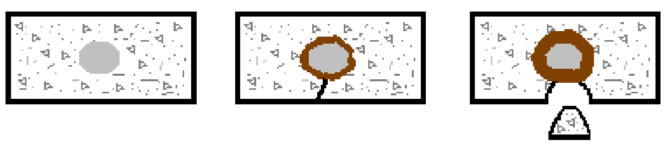

Figure 1. The process of fissuration in reinforced concrete.

The electrochemical cells that usually appear in the concrete are these: Differential Aeration Cell, Differential Saline Concentration Cell, Differential Tension Cell and Differential Temperature Cell.

The electrochemical corrosion of the steel rebars can be represented by fig. 2

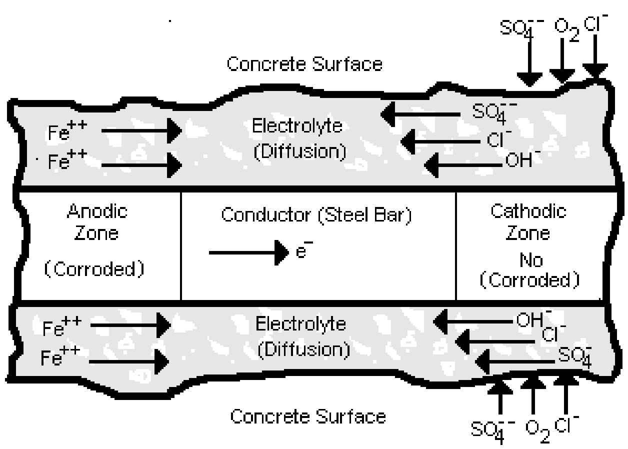

Figure 2. Corrosion Cell in Reinforced Concrete.

The reactions that occur in the anode and cathode are following:

Anodic Reactions:

$Fe \rightarrow Fe^{+2} + 2e^{-}$

$Fe^{+2} + 2(OH^{-}) \rightarrow Fe(OH)_2$ (Iron (II) hydroxide)

$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$ (Iron (III) hydroxide)

Cathodic Reaction:

$4e^{-} + O_2 + 2H_2O \rightarrow 4(OH^{-})$

3 Continuum Damage Mechanics (CDM)

The Damage Mechanics is a part of Solid Mechanics based on metallurgy, which gives a better understanding of rupture problems in structures by the definition of a variable, which represents the deterioration of the materials before the initiation of a macro-crack (LEMAITRE, 1983).

Its development began in 1958, with Kachanov (Kachanov , 1958). He introduced the first concept of a field variable called continuity modelling the loss of strength during tertiary creep. Thus, the Continuum Damage Mechanics (CDM) continued its development through the contributions of several researchers, mainly, J. Lemaitre, who published several papers that are considered as the basis for the thermodynamic formalism of constitutive modeling (PROENÇA and VENTURINI**,** 2000).

In the historical of CDM, it can be seen its growth by the increase of the application field (LEMAITRE, 2002). The CDM, in the beginning, it was used first in cases that involved creep rupture, however through the researches, nowadays, it achieved many fields of application in Engineering.

3.1 Damage Variable

Considering a damaged body. One can call a Representative Volume Element (RVE) at macro-scale, a volume element that has a size large enough to contain many defects and small enough to be considered as a material point of the mechanic of continua (KACHANOV, 1958).

Let us consider this damaged body. At a point **M** oriented by a plane defined by its normal ***n*** and its abscissa ***x*** along the direction ***n*** (LEMAITRE, 1996).

- let S be the area of the intersection of the plane with the RVE;
- let S_D be the effective area of the intersections of all micro-cracks or micro-cavities which lie in S;
- the value of the damage D(M, *n, x*) attached to the point **M** in the direction ***n*** and at the abscissa ***x*** is:

$$D(M,n,x) = \frac{S_D}{S} \tag{3}$$

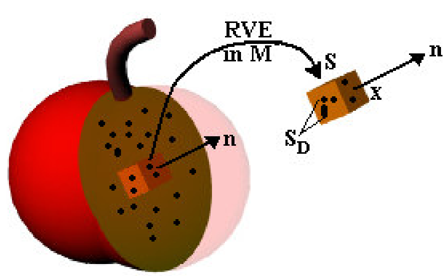

Figure 3. Damaged Element.

The effective resisting area is:

$$\tilde{S} = S - S_D \tag{4}$$

3.2 Effective Stress Concept

If a body is loaded by a force $\vec{F} = \vec{n}.F$, the usual uniaxial stress is:

$$\sigma = \frac{F}{S} \tag{5}$$

If all the defects influence the strength of body, it is convenient to introduce an effective stress $\tilde{\sigma}$ related to the surface that effectively resists the load, $\tilde{S}$

$$\tilde{\sigma} = \frac{F}{S - S_D} \tag{6}$$

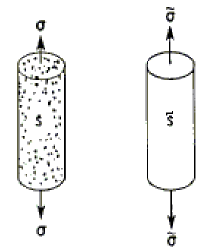

Figure 4. Picture showing representing the effective stress.

Introducing the damage variable D:

$$\tilde{\sigma} = \frac{\sigma}{1 - D} \tag{7}$$

3.3 Variation of the Elasticity Modulus

The elasticity modulus of the damaged material by the ratio $\tilde{E} = \frac{\sigma}{\varepsilon}$ is:

$$\tilde{E} = E(1 - D) \tag{8}$$

$$D = 1 - \frac{\tilde{E}}{E} \tag{9}$$

4. Materials and Methods

In this paper it was carried out a study of the process of corrosion in the damnification in steel bars CA-50A. Therefore, samples of steel bars "integrate" (no submitted to corrosion) was submitted traction test, it had been defined as standard samples, and other samples were initially submitted to accelerated corrosion test (Salt Spray), exposition in the saline fog.

Initially, twenty-one specimens of steel bar CA-50A had been confectioned, with nominal diameter of 10mm and total length (Lt) of 220mm. The useful length, Lu, (distance between machine grips in Traction Testing) is 100mm, determined according to standards NBR 7480 - 1996 and NBR ISO 6892 - 2002. Figure 5 shows a specimen and its dimensions in mm.

Figure 5. Specimens of steel bars CA-50A.

Of these twenty-one specimens confectioned, five without corrosion, it was defined with standard specimen that are reference for the analysis the evolution of corrosion process in the damnification of the material in study. The remaining specimens (16), firstly it was exposed to Salt Spray (fog) testing, and later submitted to the mechanical traction test.

4.1 Corrosion Test

The simplest test method to evaluate the corrosion (effect of aggressive ions) in reinforced concrete is the exposition in aggressive atmospheres for long time of concrete samples, with in steel inset, preparations in laboratory. However, this test can take some years to portray clearly the behavior of the steel. Alternative methods have been developed and used when information about corrosion process need to be gotten in a little time or when we need to have fast information about the tendency associated to a particular variable that is modified while others remain constant.

Very used test is the Salt Spray Test, exposition to saline fog. it was used in the development of this paper. After the confection the specimens, 16 of them were exposed to corrosion chamber of the Nucleus of Technological Development of the Ceara. This chamber can be seen in the Fig. 6.

Figure 6. Corrosion Chamber for Salt Spray Test.

The corrosion test was carried out according to standard NBR 8094 - metallic material coated and not coated corrosion for exposition in saline fog and standard ASTM 117, or either, used a 5% solution sodium chloride (NaCl) with pH of the salt spray solution enters 6,5 to 7,2 and the temperature in the zone of exposition of the chamber, was kept $(35 \pm 2)\ ^{0}C$.

The specimens were exposed in the corrosion chamber for different time. Same specimens had been taken off of the corrosion chamber with 936 hours, 2016 hours, 2376 hours and 2904 hours.

Figure 7 - Specimens after 2016 hours of exposition in the corrosion chamber.

4.2 Tension Test

With the objective to get the evolution of the damage through the variation of the elasticity modulus, agreement to Eq. (9) written by LEMAITRE for the specimens standard (not corrosion) and for the specimens submitted corrosion. Comparing the results of the specimens standard with specimens submitted corrosion, we can quantify the damage due the corrosion. Then, it was carried out mechanical test of traction “conventional” and of traction loading-unloading.

4.2.1 Conventional Tension Test

Conventional tension test were carried out in specimens (not corrosion) to determine some mechanical properties of the material as elasticity modulus, flow stress and flow deformation, maximum stress and maximum deformation. The knowledge of these characteristics of the material, CA-50A, in study are important for accomplishment of the traction test with loading-unloading. The following Figure, shows the graph stress function of the strain for this test.

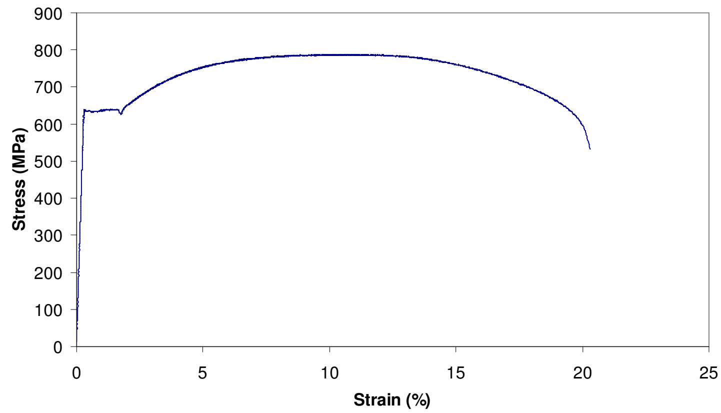

Figure 8. Graphic Stress versus Strain: Steel bar specimen (not corrosion)

4.2.2 Tension Test loading-unloading

This test has the objective to get the elasticity modulus in function of the deformation and then we can determine the evolution of the damage for each specimes, standards (not submitted to the corrosion) and for the specimes that had been exposed to corrosion. This Testing consists in application of a loading until a deformation 0.2%, followed by unloading, loading up to 1% and unloading, proceeding itself successive loading-unloading.

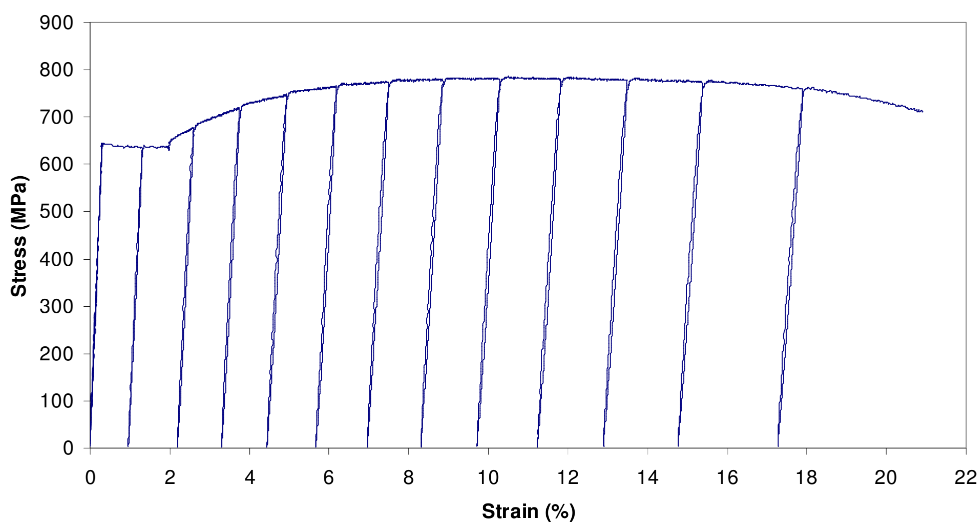

Figure 9. Graphical Stress versus Strain: Steel bar specimen (not corrosion)

5. Results and Discussion

After the realization of the tension test loading-unloading, the elasticity modulus was obtained for each unloading, then it was used the Eq. 9 for to determine the damage. The fig. 9 and fig.10 show the graphics Stress versus Strain of specimen 1 (no corrosion) and specimen 4 (with 2904 hours of exposition). The Table 1 presents the principal results of the testing, as damage of the first loading and last loading.

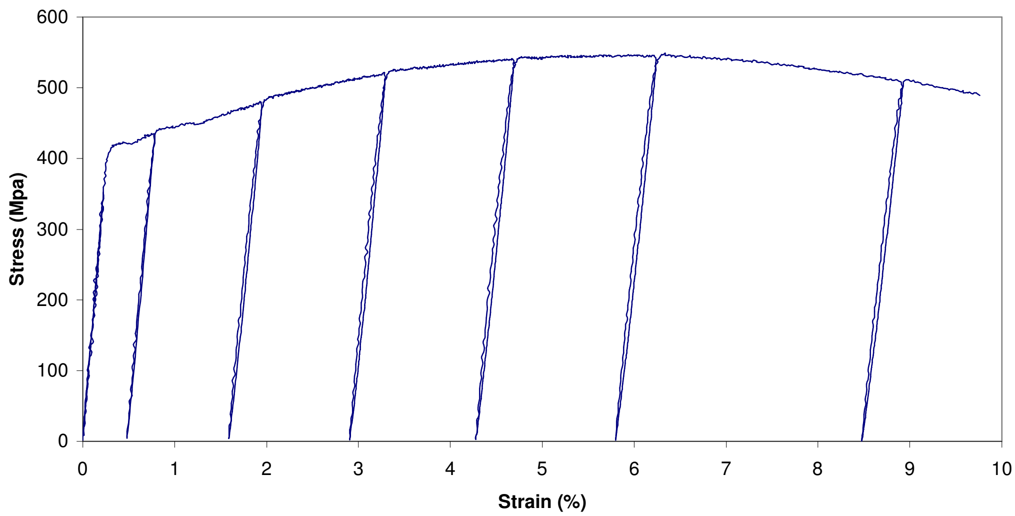

Figure 10. Graphic Stress versus Strain: specimen 4 – 2904 hours of exposition in the Corrosion Chamber

Table 1: Summary of the principal results to get tension test loading-unloading

Specimen	E_o (MPa)	Er (MPa)	D_o	Dc	σ_e (MPa)	σ_m (MPa)	ε_r (%)
1	210,3	111,8	0	0,47	642	782	17,9
2	193,8	113,7	0,08	0,46	535	677	14,1
3	166,7	109,6	0,21	0,48	484	616	13,6
4	153,1	113,0	0,27	0,46	421	546	8,9

E_o - elasticity modulus in the fisrt loading
Er - elasticity modulus in the last unloading
D_o - initial damage
Dc- critical damage (damage in the rupture)
σ_e - yield stress
σ_m - maximum stress
ε_r - strain in the rupture

The figure 11 shows the graphic Damage versus Plastic Strain of the four specimens

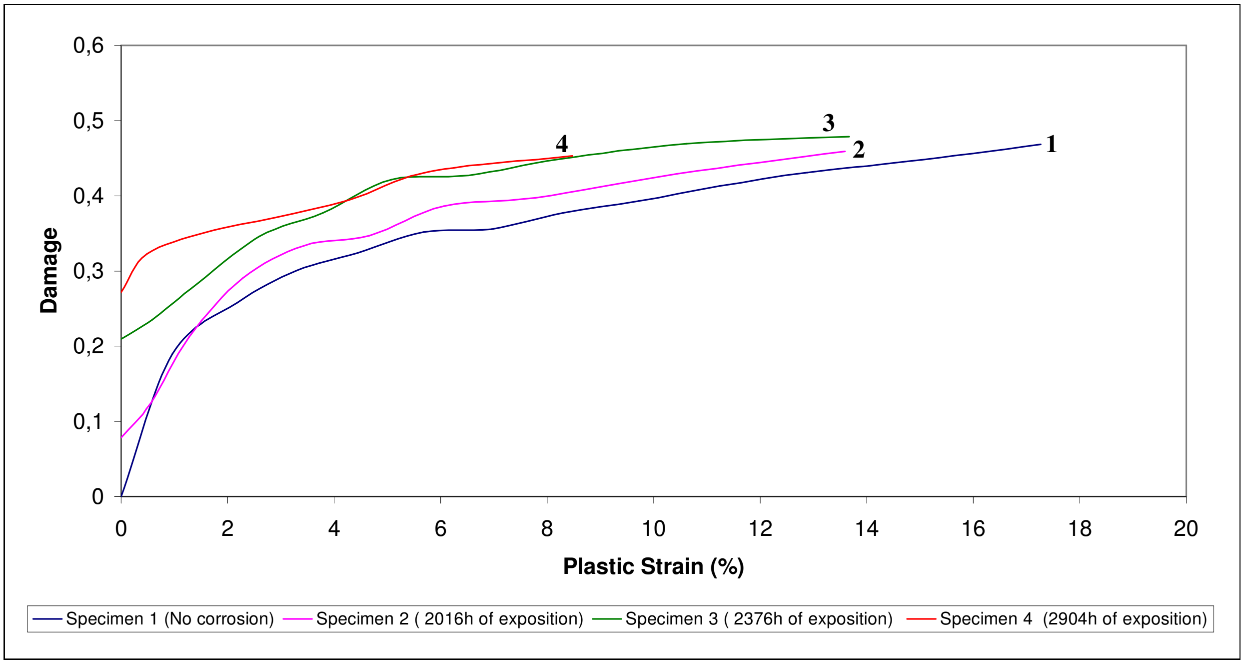

Figure 11. Graphic Damage versus Plastic Strain

6. Conclusion

The specimens exposed to corrosion presented damage in the rupture, critical damage Dc, the same of the specimen not exposed to corrosion (0,47).

The corrosion causes initial damage. The corrosion reduced yield stress, maximum stress, strain in the rupture and elasticity modulus. The specimen 4 with 2904 hours of exposition in the corrosion chamber represented a initial damage of 40% of the critical damage and a strain in the rupture 50,1% of the strain in the rupture of the specimen not exposed to corrosion.

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